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Impacts of Eutrophication on Carbon Burial in Freshwater Lakes in an Intensively Agricultural Landscape

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Abstract

The influence of inland water bodies on the global carbon cycle and the great potential for long-term carbon burial in them is an important component of global limnology. We used paleolimnological methods to estimate changes in carbon burial rates through time in a suite of natural lakes in the US state of Iowa which has watersheds that have been heavily modified over the last 150 years. Our results show increasing carbon burial for all lakes in our study as agriculture intensified. Our estimates of carbon burial rates, before land clearance, are similar to the published worldwide averages for nutrient-poor lakes. In nearly all the cases, burial rates increased to very high levels (up to 200 g C m^{-2} y^{-1}) following agricultural development. These results support the idea that the increased autochthonous and allochthonous carbon flux, related to anthropogenic change, leads to higher rates of carbon burial. Further, these results imply that the fraction of global carbon buried by lakes will be increasingly important in the future if worldwide trends in anthropogenic eutrophication continue.

Key words: carbon burial; eutrophication; paleolimnology; sediment; agriculture; global change; organic matter.

Introduction

Inland waters are increasingly being recognized as major components of the global carbon cycle, and new studies have shown that lakes are extremely active sites for transport, transformation, and storage of considerable amounts of carbon (Dean and Gorham 1998; Cole and others 2007; Battin and others 2008; Downing and others 2008). Elevated activity in these systems results in lakes affecting the global carbon cycle disproportionally to their spatial extent, and recent data have estimated that annual organic carbon (OC) burial in inland water sediments may exceed OC sequestration in the ocean by threefold (Tranvik and others 2009). Most of these studies have followed the published carbon budgets from nutrient-poor (oligotrophic) lakes (Del Giorgio and others 1997; Del Giorgio and others 1999; Duarte and Prairie 2005) which often act as CO_2 sources. Evidence from the few nutrient-rich (eutrophic) systems that have been considered in the past studies suggests that eutrophication may alter the flow of carbon in lakes (Lazzarino and others 2009; Balmer and Downing 2011).

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Differences in carbon cycling between nutrient-rich and -poor lakes may be explained because free CO_2 uptake by phytoplankton is rapid in eutrophic lakes and upsets the carbonate alkalinity equilibrium reactions (because of the slow dissociation of carbonic acid) keeping free CO_2 levels depleted with respect to atmospheric equilibrium (Stumm and Morgan 1996). Instead of diffusing to the atmosphere, dissolved CO_2 may be quickly converted to particulate OC via phytoplankton which may eventually be buried in the sediments. This suggests that eutrophic systems act as CO_2 sponges, fixing substantially greater amounts of autochthonous carbon directly from the atmosphere.

Eutrophic systems are often found within heavily modified watersheds (primarily for agriculture) (Arbuckle and Downing, 2001) where they receive increased erosional loads (Bennett and others 2001). In forested areas, temporal trends of sediment accumulation in lakes impacted by human settlement show consistent patterns of increasing sediment delivery directly after land clearance followed by a decrease and stabilization at a level still elevated above pre-clearance rates (Dearing and Jones 2003). This pattern is often attributed to catchment deforestation (for example, Davis 1976), and less is understood about temporal trends related to other land-cover types such as grasslands which may differ both in response to land clearance and initial OC concentrations within the soil (Jobbágy and Jackson 2000). Further, once land clearance takes place, there is little information available on how agricultural development directly influences the trajectory of sedimentation rates, allocthonous OC delivery, and the ability of eutrophic lakes to act as OC sinks.

Recent studies on OC burial in inland waters (for example, Downing and others 2008) have focused primarily on quantifying the total amount of OC buried in modern time periods. These studies have given important insight into the significant role of inland water bodies on global OC burial, but provide very little illumination of temporal change and the processes that control OC burial rates. We hypothesize that these processes are strongly correlated with landscape and land-use change (that is, removal of native vegetation and agricultural intensification), as well as elements of global change (that is, increasing primary production in inland waters driven by eutrophication) and propose to look at OC burial in these systems in concert with those anthropogenic effects. This will allow for better predictions of the amount of OC being buried in these systems at present and for predicting how OC burial rates in world lakes may change in the future. This study is novel in that we present complete records of OC burial in eutrophic systems with catchments that have rapidly gone from pristine grasslands to completely homogenized agricultural environments, and we pair those records with high-resolution landscape and land-use data postulated to be correlated with underlying mechanisms of change in these systems.

The aim of this study is to examine OC burial rates over time in systems that have undergone dramatic increases in watershed agriculture followed by rapid anthropogenic eutrophication. We quantify this change by adopting paleolimnological methods to estimate the time-course of OC burial in natural lakes and relating it to variables correlated with agricultural intensification, such as crop production, land development, and altered hydrology. Further, we examine the specific trajectories of the two primary OC sources from (1) autochthonous fixation through temporal trends in biogenic silica (BSi) flux, which is correlated with primary production by siliceous algae (Schelske and others 1983; Ragueneau and others 1996); and (2) allochthonous inputs through magnetic-susceptibility logging of sediment sections over time, related to the concentration of minerogenic sediments of terrestrial origin (Thompson and others 1975; Dearing and Flower 1982).

Materials and Methods

Study Area

We selected seven glacial lakes (Table 1) located in the state of Iowa in the Midwestern region of the United States. This region has been subject to some of the most intensive agricultural practices in the world, with greater than 90% of the total land area in the state of Iowa being converted to some form of agriculture over the last 150 years (Arbuckle and Downing 2001). Center Lake (CNT), West Lake Okoboji (WOK), East Lake Okoboji (EOK), Upper Gar Lake (UGR), Lake Minnewashta (MIN), and Lower Gar Lake (LGR) form a portion of a chain of lakes known as the Okoboji Chain. All six lakes share a common watershed, and all but CNT are connected by channels forming a continuous chain (Bachmann and Jones 1974). To ensure that patterns of OC burial in the chain were not being driven by localized watershed effects, we also included Silver Lake (SLV), which is hydrologically isolated from the Okoboji Chain. Spatial relationships between lakes along with major tributaries and watershed boundaries are shown in Figure 1. Lakes span a range of sizes and morphometries and

Table 1. Physical Characteristics and Selected Water Chemistry for the Seven Midwestern Lakes in This Study

Lake	Lake area (km^2)	Maximum depth (m)	TP[a] ($\mu g\ l^{-1}$)	TN[a] ($mg\ l^{-1}$)	Secchi depth[a] (m)	Chl *a*[a] ($\mu g\ l^{-1}$)
Center Lake (CNT)	1.1	4.8	96	2.0	1.6	40
West Lake Okoboji (WOK)	15.7	39.1	22	0.7	6.0	4
East Lake Okoboji (EOK)	7.5	6.4	75	1.1	2.2	14
Upper Gar Lake (UGR)	0.2	2.2	83	1.2	1.5	25
Lake Minnewashta (MIN)	0.5	4.7	84	1.2	1.9	19
Lower Gar Lake (LGR)	1.1	4.7	97	1.4	0.7	26
Silver Lake (SLV)	4.3	3.8	103	3.3	0.7	30

[a]*Mean water quality measurements for samples collected by the Iowa Lakes Survey from 2001–2009 (Downing unpublished; for details see http://limnology.eeob.iastate.edu/lakereport/).*

range in trophic status from mesotrophic to hypereutrophic (Table 1).

Sampling

Sediment cores were collected from all seven lakes in September of 2007 or June of 2008. Coring locations were chosen *a priori* from bathymetric maps (Downing unpublished; see http://limnology.eeob.iastate.edu/). One sediment core was collected from a representative location in each lake using a standard piston corer (Cushing and Wright Jr 1965). Representative basins were defined as deep (relative to the lake), flat regions. Abnormally deep areas, or ''holes,'' were avoided to minimize

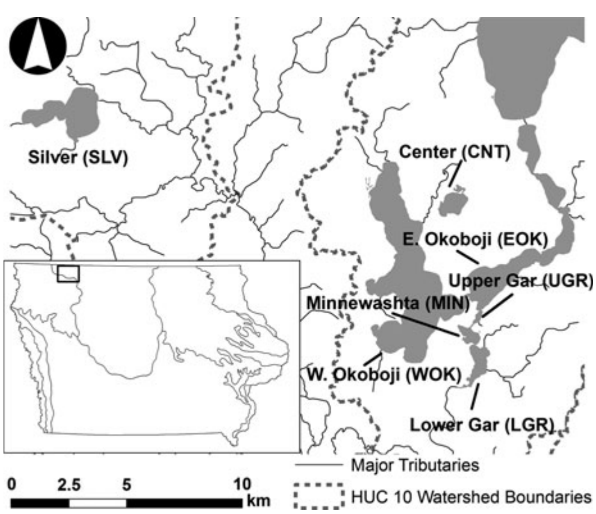

Figure 1. Geographic locations and watershed boundaries of the seven lakes sampled for this study. *Dashed lines* represent 10-digit watershed hydrologic units delineated by the USDA-NRCS (available at: http://www.igsb.uiowa.edu/nrgislibx/). *Inset* shows the location of lakes within the state of Iowa (*black box*) as well as major geologic boundaries within the state.

inflation of sediment accumulation because of focusing (Lehman 1975). Despite this precaution, multi-core studies have shown significant differences in sedimentation across space in lakes (Engstrom and Swain 1986). However, a more recent study has shown that single cores taken in this manner are reliable for interpreting significant change (for example, an order of magnitude) between lakes or over time (Rippey and others 2008). To quantify the potential for sediment focusing, we calculated the focusing-factor for each coring site. The focusing-factor is a measure of the ^{210}Pb inventory in our cores relative to values expected from average atmospheric deposition in the region (15.5 pCi m^{-2} for central North America) (Wong and others 1995). A focusing-factor equal to 1 indicates no discernible focusing at the core site, a focusing-factor less than 1 indicates sediment is focused away from the site, and a focusing-factor greater than 1 indicates some focusing has taken place. For example, a focusing-factor of 2 indicates that the core location has received twice as much sediment as would be expected from vertical flux alone (Fuller and others 1999; Lyle and others 2005). These values were not used to adjust OC burial estimates, but were provided as a means of assessing the level of bias associated with the sampling location.

The percent organic matter content of each core section was determined by loss-on-ignition (LOI) at 550°C for 1 h and converted to percent OC by multiplying by a correction factor of 0.469 (Dean 1974; Downing and others 2008; Anderson and others 2009). Samples from each core interval were sent to Daniel Engstrom at the St. Croix Watershed Research Station to be freeze-dried and analyzed for excess ^{210}Pb activity through alpha spectroscopy (Appleby and Oldfield 1978). Dates and sediment accumulation rates were calculated based on the constant rate of supply model which assumed a constant supply of ^{210}Pb to the sediment (Appleby and Oldfield 1978). OC burial was calculated as the product of the percent OC and the sediment accumulation rate at each interval.

Magnetic-susceptibility was measured using a GeoTek Standard MSCL whole-core logger at the University of Minnesota's Limnological Research Center. Magnetic-susceptibility is a measure of the amount of magnetic material present in the sediment and has been shown to be a reliable proxy for terrestrial inputs from erosional sources (Dearing and Flower 1982; Dearing and Jones 2003). We estimated the relative portion of allochthonous OC being contributed to the lake as the variance explained in OC burial by magnetic-susceptibility. The remaining portion of variance could then be attributed to autochthony or other sources of variation. OC burial was $\log_{10}$ transformed for normalization. The flocculent portion of each core was not analyzed for magnetic-susceptibility because it was removed in the field and was believed to post-date the most critical period for anthropogenic eutrophication (1850–1970) in all lakes except WOK. WOK was excluded from this analysis because magnetic-susceptibility values for the critical period were not measured.

Although all seven lakes of this study are currently mesotrophic to hypereutrophic (Table 1), it is not clear at which point and at which rate eutrophication occurred. To this end, BSi, an indicator of primary production (specifically, diatoms), was estimated as the Si:Ti ratio using whole-core X-Ray Fluorescence Spectroscopy (XRF) at 1-mm intervals in two of the lakes (MIN and LGR) (Johnson and others 2010). Similar to magnetic-susceptibility, the flocculent portion of each core was not analyzed for XRF.

Agricultural Variables

To examine the correlation between landscape change and OC burial, we followed the approach of Downing (2003) and compared OC burial rates with percent land surface in farms as an indicator of land disturbance, percent wetlands drained as an estimator of hydrologic disruption, and annual maize (*Zea mays*) yield in the state of Iowa as an index of intensification of row-crop agriculture, as well as chemical fertilization. The state of Iowa was developed rapidly and uniformly (Mutel 2008), so these broad-scale trends reflect agricultural changes within the study region.

The percent land surface in farms was determined by the United States Department of Agriculture (USDA) Census of Agriculture and was reported every 10 years between 1850 and 1930 and once every 5 years from 1930 to 2007 (U.S. Census for Agriculture, http://www.agcensus.usda.gov).

To determine the percent wetlands drained, we first estimated the area of wetlands in the state before European colonization using historical vegetation maps from the General Land Office surveyors of 1832–1859 (Anderson 1997). We then estimated the proportion of wetlands remaining from the land description data that were readily available for the following years: 1906, 1922, 1956, 1985, 1990, and 2002 (Iowa Geological and Water Survey, http://www.igsb.uiowa.edu). All the wetland areas were estimated using ArcMap 9.3 (ESRI 2008).

Maize is the primary crop in this region and comprises approximately 60% of the annual agricultural harvest (by area) making it a reliable estimator of agricultural intensification (U.S. Census for Agriculture, http://www.agcensus.usda.gov). We determined annual maize yields per unit area for the state from the USDA National Agricultural Statistics Service (NASS) which had annual data available from 1866 through 2009 (http://www.nass.usda.gov). Trends in maize yield were characterized by fitting a local polynomial regression model (LOWESS) with a span of 0.67 to the data (Cleveland and others 1992). Maize yield was used as a proxy for chemical fertilizer use because complete fertilizer records were not available over the entire time period of this study. To validate this relationship, we regressed maize yield data against the nearly three decades of fertilizer data that were available from 1981 through 2009 (Iowa Department of Agriculture, http://www.agriculture.state.ia.us), and found a significant positive correlation between the variables (Figure 2; $r = 0.56$, $P = 0.001$, $n = 29$).

Analytic Methods

Relationships between OC burial and landscape change were determined using Pearson's correlation coefficient. Agricultural variables available were statewide estimates and were compared to the average OC burial for all lakes ($n = 7$) rather than each lake individually. This approach was used to avoid predicting multiple burial rates from a single landscape variable. Maize yield was compared to average OC burial by predicting OC burial at 15-year intervals from 1870 to 2005 ($n = 10$) using locally weighted regression (LOWESS) (Cleveland and others 1992). The percent area in farms ($n = 25$) and percent wetlands drained ($n = 7$)

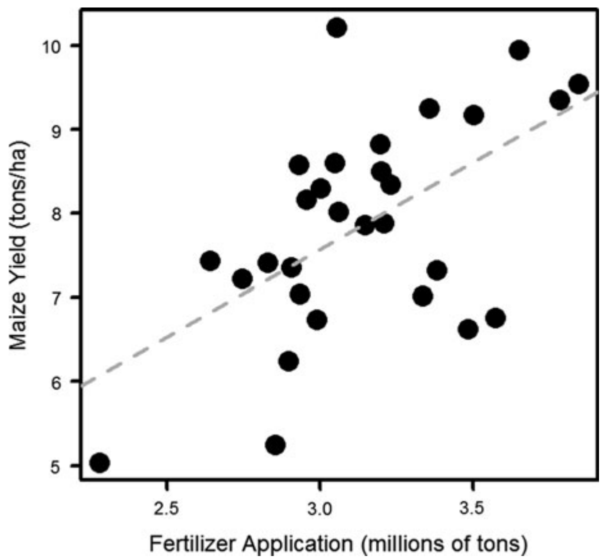

Figure 2. Annual maize yield plotted against annual fertilizer application for the region demonstrating the significant positive correlation between the variables ($r = 0.56$, $P = 0.001$).

were reported at intermittent time intervals, and so we used the average of OC burial in all years within each time interval. OC burial was normalized using a $\log_{10}$ transformation.

We examined the difference between pre-settlement and modern OC burial by calculating discrete estimates of OC burial in each lake before European settlement (hereafter referred to as historic) and at the time of sampling (hereafter referred to as modern). The year 1850 was chosen as a reference point for historic conditions because most published census data indicate that the region was not extensively cultivated for agriculture until at least 15 years later (Van Zant and others 1979). A paired *t*-test was performed to test that OC burial was significantly higher in the modern samples and to ensure that variation in OC burial between time periods (modern vs historic) was greater than the variation among lakes.

In addition to the data collected in this study, we compared our results to OC burial data collected in 92 different lakes and impoundments across the world (Mulholland and Elwood 1982; Downing and others 2008; Sobek and others 2009; Biggs unpublished).

Results

Dating and Single Core Validation

All seven lakes were successfully dated using the ^{210}Pb constant rate of supply model. These dates confirmed that each core was representative of the period before and after agricultural intensification in the region. The oldest ^{210}Pb dates in all but UGR preceded 1850. The oldest dated section for UGR was still within one standard error of 1850 (1869 ± 30 years), and so this section was also assumed to be representative of historic OC burial rates. Sediment focusing-factors were less than 2 for all cores except MIN, which had a focusing-factor of 3.5 (Table 2). Three of the sediment cores had focusing-factors which were less than 1. The average focusing-factor for all the seven lakes was 1.6.

^{210}Pb dates were significantly correlated ($P < 0.001$) with average OC burial rates ($r = 0.93$ $n = 10$) (Figure 3), indicating that OC burial

Table 2. Sediment Focusing Factors for all Seven Sediment Cores Illustrating the Approximate Amount of Sediment Focusing to or Away from the Coring Site

Lake	^{210}Pb inventory (pCi cm^{-2})	Focusing-factor
CNT	29.5	1.9
WOK	25.4	1.6
EOK	29.6	1.9
UGR	9.0	0.6
MIN	53.5	3.5
LGR	13.6	0.9
SLV	9.3	0.6

Atmospheric ^{210}Pb deposition was assumed to be 15.5 pCi cm^{-2}.

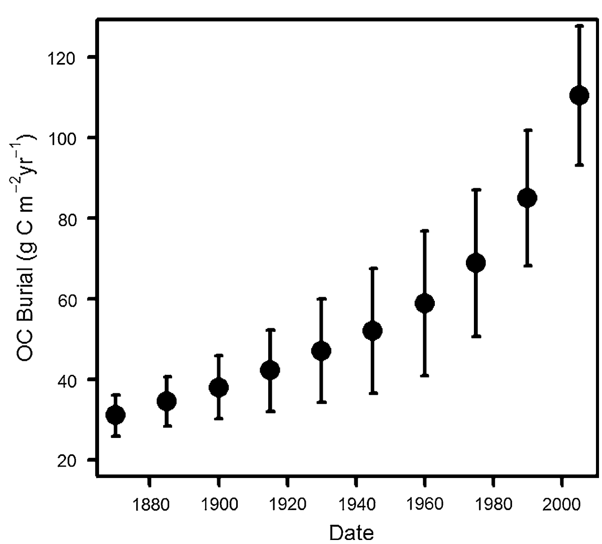

Figure 3. Relationship between year and OC burial in seven lakes from the Midwestern U.S. ($r = 0.93$, $P < 0.001$, $n = 10$). Points are average OC burial rates for all seven lakes estimated from LOWESS regression. *Error bars* represent ±1 SE.

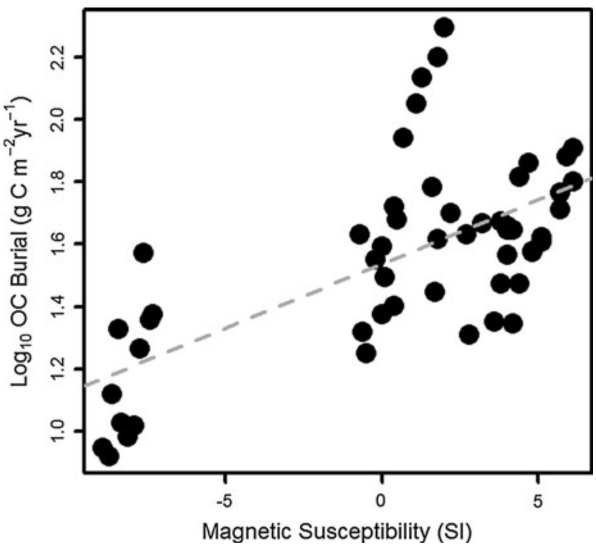

Figure 4. OC burial plotted against magnetic susceptibility. Forty-two percent of the variance in OC is explained by allocthonous inputs ($r = 0.65$, $P < 0.001$, $n = 53$).

increased over time. OC burial had a significant positive correlation with magnetic-susceptibility, a proxy for terrestrial inputs, ($r = 0.65$, $P < 0.001$, $n = 53$), which indicated that 42% of the variation in OC burial was related to increasing inputs from allochthonous OC sources (Figure 4). BSi flux, a proxy for primary production by phytoplankton, showed asymptotic increases over time in both lakes in which it was measured (MIN, LGR) (Figure 5), indicating steady increases in primary production over time for both systems. These increases began shortly after settlement (~ 1850), but become more pronounced at the beginning of the twentieth century, with markedly larger increases in MIN after 1900 and steady increases in LGR after 1920.

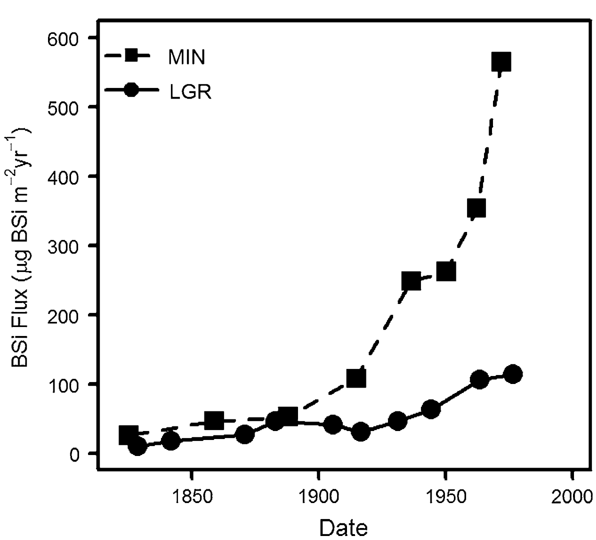

Figure 5. Temporal trends in BSi flux (a proxy for autochthonous primary production and eutrophication) for MIN and LGR, illustrating asymptotic increases following settlement.

Impacts of Landscape Change on OC Burial

All three of the agricultural variables reflected the rapid transformation of native land to use for agriculture (Figure 6). By 1900, 83% of the land in the state was farmland, and 96% had been converted by 1950. The percent of wetlands drained tripled from 22% in 1900 to 69% in 1922. Ninety percent of the wetlands in the state were drained by 1956. The average maize yield for each decade from 1860 to 1930 remained fairly constant (range: 2.12–2.49 t/ha), but increased in each decade following 1940 to a maximum of 10.25 t/ha in the 2000s. All three agricultural variables had a significant positive correlation with the average OC burial for all seven lakes (Table 3). Percent wetlands drained and annual maize yield explained a relatively large proportion of the variation ($r^2 = 0.76$, 0.94) in comparison to percent land in farms ($r^2 = 0.19$).

Historic versus Modern OC Burial Comparison

Changes in OC burial ranged from +39 to +162 g C m^{-2} y^{-1} (Table 4), and the average difference (modern − historic) was 85 ± 39 g C m^{-2} y^{-1} ($t = 5.31$, $n = 7$, $P = 0.002$).

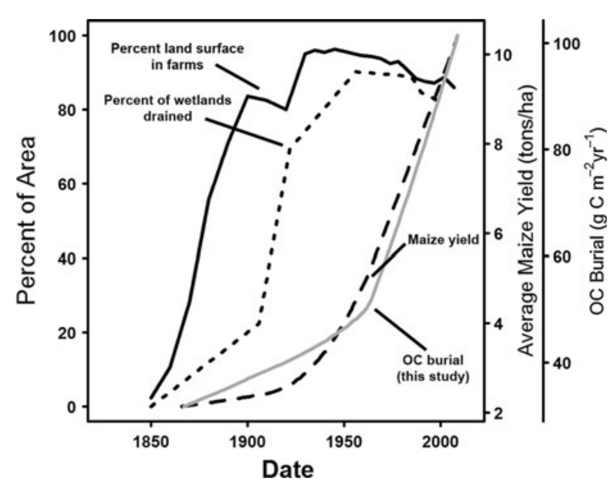

Figure 6. Agricultural variables for the region plotted over time for the last century and a half. Agricultural data are overlaid by the LOWESS trend for the average OC burial over all lakes. Agricultural data modified from Downing (2003), with permission.

Table 3. Correlation Coefficients (r), Sample Size (n), and Significance (P) for Three Agricultural Variables Against Average OC Burial Rates for Seven Midwestern Lakes

Agricultural variable	r	n	P
Percent land in farms	0.44	25	0.035
Percent wetlands drained	0.87	7	0.010
Annual maize yield	0.97	88	<0.001

OC burial rates from the published worldwide data were summarized as 95% confidence regions for mean values of OC burial versus lake area (Figure 7). Historic OC burial rates from this study all fell within or below the 95% confidence region estimated for natural lakes of similar size (lake area < 100 km^2) using data from Mulholland and Elwood (1982). All historic OC burial rates were below Mulholland and Elwood's published mean for mesotrophic and eutrophic lakes (94 g C m^{-2} y^{-1}), and approximately 60% of the historic rates in this study fell below the published mean for oligotrophic lakes (27 g C m^{-2} y^{-1}). Modern OC burial rates from six of the seven lakes in this study fell above the 95% confidence region for natural lakes, and about 70% fell above the published mean for mesotrophic and eutrophic lakes. None of the modern rates of OC deposition fell below the published mean for oligotrophic lakes.

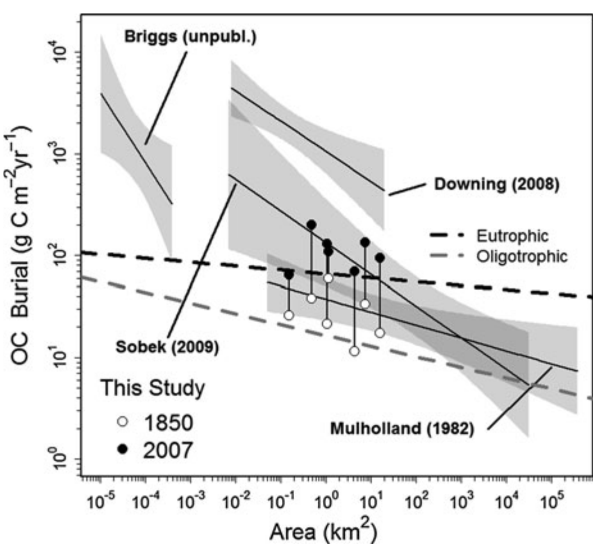

Figure 7. Data from a worldwide sample of lakes and reservoirs are presented as 95% confidence regions for the mean relationships between OC burial rates and surface water area, calculated from previous studies (Mulholland and Elwood 1982; Downing and others 2008; Sobek and others 2009; Briggs unpublished). Points represent historic (*empty*) and modern (*shaded*) OC burial rates in seven lakes from the Midwestern U.S. *Dashed lines* represent average burial rates in natural lakes from Mulholland and Elwood (1982) split between oligotrophic (*black line*) (mean: 27 g C m^{-2} y^{-2}) and mesotrophic/eutrophic (*grey line*) (mean: 94 g C m^{-2} y^{-2}).

Discussion

Impacts of Landscape Change on OC Burial

Our data support the hypothesis that landscape change and eutrophication resulting from agricultural intensification were associated with increasing OC burial in these inland waters. Using variables that represent agricultural intensification within the watershed (for example, percent wetlands drained, maize yield, and so on) along with proxies for autochthonous primary production (BSi) to estimate eutrophication, our data show a highly significant correlation between OC burial and increases in agricultural intensification.

Our results indicate nearly half (42%) of the increase in OC burial in these systems is statistically attributable to fluctuations in our proxy of allochthonous inputs (magnetic-susceptibility; Figure 4). This result is not surprising because this region has lost approximately half of its OC-rich topsoil (20 cm on average) in the last 150 years (Risser 1981). A majority of these soil losses have been transported downstream and are linked to the extremely high OC burial rates already documented in impoundments of the region (Downing and others 2008). It is likely that these natural lakes are, likewise, receiving similarly large loads of suspended sediments, making up a significant portion of the OC buried in these systems.

The increasing BSi fluxes seen in the two lakes in this study reflect only phytoplankton which form siliceous structures, primarily belonging to the class Bacillariophyceae (diatoms) and to a lesser extent Chrysophyceae. These two classes make up a large portion of the total phytoplankton biomass at low and intermediate nutrient concentrations (0–50 µg/l TP), but become decreasingly abundant relative to other phytoplankton, specifically Cyanobacteria, at higher nutrient concentrations (Watson and others

1997). Because both lakes for which BSi flux was measured have average TP concentrations greater than 50 μg/l (Table 1), it is likely that changes in BSi flux underestimate the change because of total phytoplankton primary production following eutrophication. Increases in autochthonous fixation and burial of autochthonous OC may be even greater than implied by Figure 5.

Although BSi may underestimate the magnitude of change in total primary production at high nutrient concentrations, the trend toward increasing primary production is clear, and it is most likely due to anthropogenic eutrophication. Primary production remained fairly constant before European settlement and has increased asymptotically since then (Figure 5). Though MIN and LGR had differing trajectories in BSi over time, the greatest increase in both lakes was post-1950, when more intensive agricultural techniques became prevalent in the region (Auclair 1976). Increasing primary production would result in increasing autochthonous OC fixation by primary producers and an increasing role for these systems in fixing and burying atmospheric carbon.

Contrary to some other studies (for example, Davis 1976; Jones and others 1985), the greatest increase in OC burial did not occur directly after initial land clearance. Instead, OC burial was more closely correlated with increasing maize yields ($r = 0.97$) and wetland drainage ($r = 0.87$) which peaked nearly a century after European settlement (Figure 6). This implies that changes in OC burial rates were more influenced by the intensification of agricultural practices (for example, row-cropping, tillage practices, chemical fertilization, and artificial drainage) which occurred in the mid-twentieth century rather than by initial clearance and conversion of native vegetation. Previous studies considering temporal changes in sedimentation rates (for example, Davis 1976; Jones and others 1985) have primarily considered historically forested landscapes which, when cleared for timber or other uses, may be left barren for a time and be more susceptible to large erosional events. Conversely, native grasslands, (such as those that formerly surrounded the lakes in this study), were cleared for agriculture and then quickly cultivated with cover crops (usually cereals) which could provide protection and stability to the soil (Mutel 2008). Also, timber harvest rotations keep some cover over periods spanning decades, whereas grasslands converted for agriculture are annually stripped of their vegetation. This may explain the large cumulative contribution of allochthonous OC seen in this study relative to studies of forested landscapes.

Historic versus Modern OC Burial

On average, lakes in this study increased OC burial by 4.5-fold following eutrophication (Table 4). Variation in morphometry and size among the lakes likely accounted for a portion of the variance in historic and modern burial rates; however, the among-lake variation was small compared to the average change in OC burial seen between time periods (85 ± 39 g C m^{-2} y^{-1}, $P = 0.002$).

When data from this study are compared with published OC burial rates in similar systems worldwide (for example, Mulholland and Elwood 1982), the contrast between historic and modern OC burial rates is apparent. Historic OC burial rates for the seven lakes in this study all fell in or below the 95% confidence region for the OC burial data from world lakes (Mulholland and Elwood 1982). This suggests that OC burial rates for our lakes were in line with predicted averages for mesotrophic and oligotrophic lakes before disturbance. In all but one of these lakes (UGR), modern OC burial rates have shifted above the 95% confidence region for the world lake OC burial data. Six of these lakes are now eutrophic or hypereutrophic (TP > 50 μg l^{-1} or TP > 100 μg l^{-1}, respectively), and none would be classified as oligotrophic (TP < 10 μg l^{-1}) (Table 1).

Although only seven lakes were considered here, lakes throughout the agricultural Midwest have experienced similar levels of anthropogenic eutrophication (2007 mean TP concentration for Iowa lakes and reservoirs: 112 ± 10 μg l^{-1}, $n = 121$; Downing unpublished). If there is a generalized relationship between OC burial and eutrophication, then OC burial in continental waters is likely increasing systematically with increased nutrient concentrations and eutrophication.

Extrapolating Single Cores to Whole-Lake Estimates of OC Burial

Caution must be used when extrapolating OC burial from a single sediment core across an entire lake. Recent studies have suggested that a minimum of 5–10 cores should be taken when trying to precisely estimate whole-lake sediment and OC burial rates; however, a single central core has still been shown to be able to establish large-scale differences in OC burial between lakes (Rowan and others 1995; Rippey and others 2008). The sediment focusing-factors from our seven cores indicate that some horizontal flux of sediment occurred, especially at MIN, which may have led to some overestimation of OC burial in those systems. Three of the systems had focusing-factors less than 1

Table 4. Comparison of Historic and Modern OC Burial Rates in Seven Midwestern Lakes

Lake	Historic OC burial[a] (g C m^{-2} y^{-1})	Modern OC burial[b] (g C m^{-2} y^{-1})	Δ OC burial (g C m^{-2} y^{-1})
CNT	60	110	50
WOK	17	95	78
EOK	33	135	102
UGR	26	64	38
MIN	38	200	162
LGR	21	130	109
SLV	12	70	58

[a]*Historic OC burial estimated for the year 1850.*
[b]*Modern OC burial estimated for the year 2007.*

which would indicate sediment focusing away from the site (unlikely due to core site location) or ^{210}Pb outflow due to shorter water residence times. Because our data were presented as averages across all cores in this study (for example, Figures 3 and 6), we have minimized potential bias because of any extreme values attributed to focusing (to the site or away from it) and brought our OC burial rates closer to what might be expected to represent an average whole-lake estimate. The mean focusing-factor for these cores was 1.6, indicating that horizontal flux of sediment was less than the expected vertical flux (focus-factor <2), on average, at these sites.

In the future, it may be reasonable to use focusing-factors as a means of correcting for sediment focusing in single cores, but this would complicate comparisons with OC burial numbers reported in other studies (for example, Mulholland and Elwood 1982; Downing and others 2008; Sobek and others 2009) which were not corrected in a consistent manner. We felt that not transforming the OC burial, while still reporting the individual focusing factors for each core, was the approach involving the fewest assumptions. All OC burial results from our study were in line with estimates generated from the other studies using more intensive and time-consuming methods such as intensive coring and repeated bathymetry (Mulholland and Elwood 1982; Downing and others 2008; Sobek and others 2009).

Conclusions

Owing to increasing world population and consumption, nearly all of the remaining cultivatable land will be converted to intensive agriculture in as little as 50 years (Tilman and others 2001). If current trends hold, then this conversion will be accompanied by increasing eutrophication and the nutrient-driven degradation of water quality by agricultural nutrient effluent (Carpenter and others 1998; Arbuckle and Downing 2001). The most recent published data of carbon budgets estimate global OC burial by inland waters at 0.6 Pg/year (Tranvik and others 2009). If agricultural intensification leads to an eventual doubling of OC being buried worldwide (the minimum total increase seen in this study), then this additional carbon must represent a substantially increased contribution from terrestrial sources or decreased evasion of carbon to the atmosphere. In either case, if anthropogenic eutrophication continues, inland waters will play an increasingly important role in the long-term burial and storage of OC.

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